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Experimental study on the decision-making and motion behavior of subgroups when facing a static obstacle during movement

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ABSTRACT

The interaction between pedestrians and obstacles is an interesting research topic in pedestrian and evacuation dynamics. Many studies on this topic have treated single individuals or human crowds as objects and have drawn a lot of research findings. However, as an intermediate layer linking the individual and group levels, subgroups have rarely been considered in such studies, and little is known about their behavioral mechanisms when interacting with obstacles. From this, we want to understand how certain key factors affect the decision-making and motion behavior of subgroups when facing a static obstacle during movement. Here, we organize a series of controlled experiments, in which the obstacle width, time pressure, and subgroup size serve as three control variables to create various experimental conditions. The analysis of the experimental data shows that a wider obstacle width, a more urgent time pressure, and a larger subgroup size correspond to a higher proportion of the splitting–merging state. The strong right-side preference emerges in the maintaining state, but the movement preference in the splitting–merging state largely depends on the difference in subgroup sizes. The path lengths in the splitting–merging state are longer than those in the maintaining state, but no significant difference exists in movement times between the two movement states. The conclusion that the average speeds decrease with increasing subgroup size at normal densities can be extended to most conditions of different obstacle widths, time pressures, and movement states. Besides, the three control variables have various influence degrees on centroid positions, movement times, and average speeds in the splitting and merging processes, and the herding effect of subgroup members can be observed in the merging process. Overall, these findings may advance the understanding of subgroup behaviors and support the development of subgroup models.

1. Introduction

Pedestrian and evacuation dynamics have become an important research field over the last two decades (Helbing & Johansson, 2009), with relevant achievements being widely applied in transportation science, architectural design, and safety management (Dong et al., 2020). Throughout many studies in this field, however, human crowds are often regarded as composed of isolated individuals by following simple assumptions, which are contrary to the prevalence of subgroups (note that this is a collective term for "social groups", "pedestrian groups", and "small groups" in other literature) in real-world situations (Nicolas & Hassan, 2021). Since subgroups receive increasing attention as a key research topic, they have spawned a series of research findings. Undoubtedly, subgroups are considered to move in a congregated form in most cases (Moussaïd et al., 2010; Wu et al., 2023), but in certain cases (e.g., when facing obstacles, when crowd density changes), special movement states (e.g., splitting–merging) may appear (Do et al., 2016; Singh et al., 2009). However, few studies related to this have been conducted, and most of them still remain at the level of qualitative descriptions (Wu & Zheng, 2023). Many reviews in this field suggest that as one of the most crucial means for extracting data (Feng et al., 2021; Haghani & Sarvi, 2018), the experimental study is significant for excavating the laws of phenomena and behaviors, as well as for guiding the modeling process and evaluating the performance of models. As a consequence, it is worth utilizing relevant experiments to study the decision-making and motion behavior of subgroups in specific contexts, such as interacting with obstacles.

The latest survey indicates a growing trend year by year for experimental studies on the topic of subgroups. In terms of observational experiments, Jazwinski and Walcheski (2011) conducted five naturalistic observational studies at a shopping mall and found that both larger subgroups and larger numbers of children independently increase the

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walking time of pedestrians. Duives et al. (2014) studied the video material of bidirectional crowd movements in a bridge to conclude that the size and composition of age and gender within a subgroup will affect the movement dynamics of the entire subgroup. Fu et al. (2019) indicated that the subgroup size has a significant impact on both walking patterns and average speeds by observing 105 pedestrian subgroups descending the stairs in a university campus. Gorrini et al. (2019) analyzed the video recordings at a non-signalized intersection and argued that the crossing behavior of subgroups is based on the emergence of a leader who decides to cross first, followed by the companion. With regard to controlled experiments, Bode et al. (2015) organized evacuation experiments with subgroups escaping from a multi-exit room and showed that the presence of subgroups increases egress time due to differences in response times and movement dynamics. von Krüchten and Schadschneider (2017) carried out evacuation experiments with subgroups of different sizes and interactions and found that large subgroups may reduce evacuation time due to self-ordering effects. Haghani et al. (2019) investigated the effects of subgroup size and stress level on multiple aspects such as pre-movement time, decision time, exit-choice behavior, and subgroup decision dynamics based on field evacuation experiments. Lombardi et al. (2020) found that both contextual and personal factors contribute significantly to the emergence of a leadership role through experiments with a small walking subgroup. Xie et al. (2020) conducted evacuation experiments indoors with different visibility and discovered that subgroup behaviors have a negative impact on evacuation in normal visibility, but a positive impact in lower visibility situations. Hu et al. (2021) revealed that subgroups barely change the speed-density relationship at the macroscopic level, but strongly affect operational behaviors at the microscopic level by incorporating subgroups in unidirectional pedestrian flow experiments. Ye et al. (2021) implemented a series of controlled experiments in a ring-shaped corridor to study the traffic dynamics of unidirectional and bidirectional pedestrian flows involving dyad subgroups. Ren et al. (2022) studied the behavioral patterns of subgroups in evacuation experiments and found that the presence of subgroups inhibits the evacuation efficiency, whose degree is related to the proportion of subgroups. Fu et al. (2022) adopted controlled experiments to analyze the movement features of subgroups passing through a bottleneck with different widths, and compared the behavioral differences between individuals and subgroups. These studies mostly focus on analyzing the explicit characteristics (e.g., subgroup size, walking speed, and spatial configuration) of subgroups under natural conditions, and exploring the effects of their decision-making and motion behavior on self-organization phenomena and evacuation processes in typical scenarios such as single-exit (or multiple-exit) rooms, circular (or ring) areas, unidirectional (or bidirectional) corridors, and bottlenecks. Nevertheless, the interaction between moving subgroups with obstacles has almost never been considered, leaving research findings on the decision-making and motion behavior of subgroups in such contexts remain unsettled.

Turning now to experimental studies on pedestrian-obstacle interactions, which have been of considerable interest. Moussaïd et al. (2009) performed well-controlled experiments on pedestrians dealing with simple avoidance tasks and described the average change in direction and speed of pedestrians for various interaction distances and angles by computing behavioral maps. Jiang et al. (2014) utilized evacuation experiments with pillar obstacles to validate the simulation results that appropriately placing two pillars on both sides but not in front of the door would maximize the escape efficiency. Li et al. (2019) indicated that the choice of pedestrians around obstacles is related to the difference in distance between exit route starting points and crowd density along routes by field observations and virtual experiments. Jia et al. (2019) conducted experiments to analyze the obstacle evading behavior of pedestrians and found that the growing obstacle width hardly affects the frequency and amplitude of body sway, but leads to a substantial increase in the lateral deviation of walking direction. Shi et al. (2019) investigated the impact of different geometrical layouts at the exit on pedestrian flows based on controlled experiments and summarized that the effectiveness of the obstacle is sensitive to its size and distance from the exit. Chen et al. (2019) pointed out that the concave layout is more conducive to pedestrian movement by analyzing the movement characteristics under the experiments of parallel, convex, and concave obstacle layouts. Ding et al. (2020) explored the impact of different obstacles on crowd dynamics via evacuation experiments and found that the evacuation times in crossable obstacle cases are basically longer than those in passable obstacle cases. Zhao et al. (2020) designed evacuation experiments under different types of obstacles and suggested that the evacuation efficiency is sensitive to the geometrical parameters of obstacles and can be promoted by arranging obstacles properly. Wang et al. (2020) concerned the impact of temporary obstacles on pedestrian dynamics in controlled experiments, showing that the right-side preference during obstacle avoidance can be observed and a temporary stop close to the boundary is better than that in the middle of the corridor. It can be summarized that the above studies mainly concentrate on exploring the effects of obstacle characteristics (e.g., shape, type, and layout) on pedestrian behaviors (e.g., avoidance maneuver, path selection) and traffic efficiencies (e.g., pedestrian flow, evacuation time). However, the objects interacting with obstacles in these studies are basically single individuals or human crowds, which results in little attention being paid to the interaction between moving subgroups with obstacles. More critically, it is necessary to conduct relevant research due to the significant differences between subgroups and these objects in terms of size and composition, coordination degree, and intentionality in navigating to pass through obstacles.

Therefore, this work designed a series of controlled experiments on the decision-making and motion behavior of subgroups when facing a static obstacle during movement. Specifically, we placed a retractable static obstacle in the middle of a rectangular scenario, and allowed randomly combined subgroups to start from the initial area and move to reach the terminal line within a certain time. By adjusting different values of the three control variables: obstacle width (2 m, 3 m, and 4 m), time pressure (+∞ s, 8 s, and 5 s), and subgroup size (2, 3, and 4), we conducted 12 rounds for each of the 27 experimental groups under different conditions and extracted pedestrian trajectories using an open source software. First, the decision-making (i.e., movement states and preferences) of subgroups during movement was investigated. Then, the motion behavior of subgroups when facing a static obstacle was further explored, especially for the differences in physical quantities (i.e., path length, movement time, and average speed) between the maintaining and splitting–merging states. Last, we analyzed the centroid positions, movement times, and average speeds of subgroup members in the splitting and merging processes, and also considered the effects of the movement preference on the two processes. The related findings are expected to pave the way for the understanding of subgroups interacting with obstacles and provide empirical evidence for the establishment of more realistic subgroup models.

The rest of this paper is organized as follows. Section 2 describes the experimental details and data acquisition. In Section 3, the research findings are obtained by analyzing the experimental data. Finally, the main conclusions and potential values are summarized in Section 4.

2. Methods

2.1. Experimental settings and procedures

The purpose of our experiments was to study the decision-making and motion behavior of subgroups when facing a static obstacle during movement. These experiments were implemented on April 9th, 2023 at the Central Main Building of Tsinghua University in Beijing, China. A total of 12 university students (8 males, 4 females) were invited as participants and their ages ranged from 23 to 28 years old. All

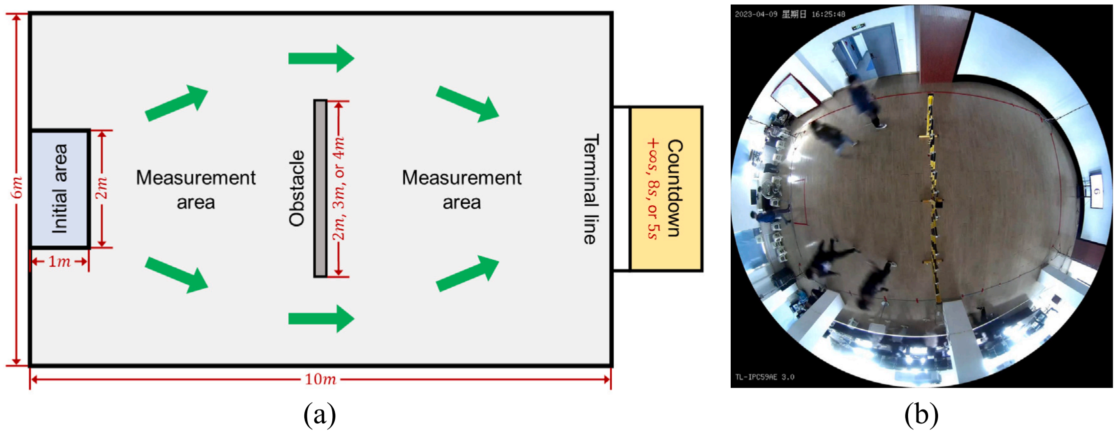

Fig. 1. Experimental scenario and snapshot. (a) The schematic diagram of the experimental scenario. (b) The snapshot at a certain moment in the collected video.

Table 1
Control variables involved in the experiments.

Control variable	Symbol	Value	Specific implication
Obstacle width	W	2 m 3 m 4 m	Relatively narrow Relatively medium Relatively wide
Time pressure	T	$+\infty$ s 8 s 5 s	Non-emergency Mild emergency Severe emergency
Subgroup size	S	2 3 4	Two members Three members Four members

participants signed the informed consent form before the start of experiments, and none of them reported any physical health impairments. Each participant was assigned one of the labels numbered 1 to 12, and a computer program was used to make multiple non-repeating combinations (i.e., generating 6, 4, and 3 combinations of labels each time for subgroups of 2, 3, and 4 members, respectively) to randomly create subgroups. Under various combinations of these labels, subgroup members might or might not be familiar with each other, but were all told to behave in a manner similar to subgroups with relatively moderate social relationships in real-world situations. This kind of social relationship falls between relatively weak social relationships between strangers and relatively strong social relationships between family members. Note that the implementation of our experiments was approved by the Ethics Committee of Tsinghua University.

The experimental scenario was a 10 m × 6 m rectangular area, whose schematic diagram is illustrated in Fig. 1(a). Here, a small 2 m × 1 m rectangular area at the left center position was the initial area (light blue), which was used to gather subgroup members together before each round of experiments. A retractable barrier fence placed in the middle of the scenario was considered as a static obstacle (dark gray) and its width could be arbitrarily altered. The right boundary of the scenario served as the terminal line, behind which a large display screen (light yellow) was erected to provide participants with a countdown in each round of experiments. The remaining portion of the scenario (light gray) was the measurement area for pedestrian movement, and green arrows implied possible movement tendencies. Before the start of each round of experiments, participants were informed to form subgroups with others and gather in the initial area according to the assignment from an organizer. Then, the other organizer immediately initiated the start instruction for each round, and subgroup members spontaneously decided for themselves how to pass the static obstacle, but should reach the terminal line in as congregated a form as possible before the countdown to zero. At the end of each round of experiments, each member would be rewarded with 3 RMB in this round if all subgroup members reached the terminal line within the given time, otherwise, none of them would be rewarded.

Table 2
Specific details of the experimental settings.

Experimental group	Obstacle width	Time pressure	Subgroup size	Round
W1-T1-S1	2 m	$+\infty$ s	2	12
W1-T1-S2	2 m	$+\infty$ s	3	12
W1-T1-S3	2 m	$+\infty$ s	4	12
W1-T2-S1	2 m	8 s	2	12
W1-T2-S2	2 m	8 s	3	12
W1-T2-S3	2 m	8 s	4	12
W1-T3-S1	2 m	5 s	2	12
W1-T3-S2	2 m	5 s	3	12
W1-T3-S3	2 m	5 s	4	12
W2-T1-S1	3 m	$+\infty$ s	2	12
W2-T1-S2	3 m	$+\infty$ s	3	12
W2-T1-S3	3 m	$+\infty$ s	4	12
W2-T2-S1	3 m	8 s	2	12
W2-T2-S2	3 m	8 s	3	12
W2-T2-S3	3 m	8 s	4	12
W2-T3-S1	3 m	5 s	2	12
W2-T3-S2	3 m	5 s	3	12
W2-T3-S3	3 m	5 s	4	12
W3-T1-S1	4 m	$+\infty$ s	2	12
W3-T1-S2	4 m	$+\infty$ s	3	12
W3-T1-S3	4 m	$+\infty$ s	4	12
W3-T2-S1	4 m	8 s	2	12
W3-T2-S2	4 m	8 s	3	12
W3-T2-S3	4 m	8 s	4	12
W3-T3-S1	4 m	5 s	2	12
W3-T3-S2	4 m	5 s	3	12
W3-T3-S3	4 m	5 s	4	12

The manipulations of our experiments involved three control variables: obstacle width, time pressure, and subgroup size (see Table 1). First, the obstacle width (W) was set to 2 m, 3 m, and 4 m (i.e., with the ratio of 1/3, 1/2, and 2/3 to the scenario width), corresponding to the relatively narrow, medium, and wide situations, respectively. This ensures that there is an obvious blocking effect and also allows enough space on both sides for pedestrians to pass. Second, the time pressure (T) was given as $+\infty$ s, 8 s, and 5 s to represent the non-, mild, and severe emergency situations, respectively. That is, pedestrians just need to walk at a normal speed without considering time constraints in non-emergency situations, but have to reach the terminal line at average speeds of at least higher than 1.125 m/s and 1.8 m/s (i.e., the minimum path length divided by the maximum movement time) in mild and severe emergency situations, respectively. Third, the subgroup size (S) was fixed as 2, 3, and 4, determined by empirical evidence that subgroups composed of two to four members are the most common in reality (Moussaïd et al., 2010). According to these control variables and their values mentioned above, we set up a total of 27 (3 × 3 × 3) experimental groups under different conditions, whose specific details are summarized in Table 2. It should be emphasized that 12 rounds with various label combinations of subgroups under each experimental group were performed to obtain statistically significant results.

2.2. Data collection and extraction

To record the movement process of subgroups in our experiments, a surveillance device was installed on the top ceiling corresponding to the center of the experimental scenario, approximately 3 m above the ground. Due to the height limitation of indoor installation, a TP-LINK panoramic fisheye camera (TL-IPC59AE) was selected to ensure the coverage of the whole scenario. The video was captured with a frame rate of 25 FPS and a resolution of 2888 × 2888 pixels. This fisheye camera collected the video of our experiments from 14:06 to 16:28 on April 9th, 2023, and Fig. 1(b) displays the snapshot at a certain moment in the collected video. For facilitating the analysis, the videos of 27 experimental groups were cut out, with each including the clips of 12 rounds. From this, we segmented a total of 324 (27 × 12) video clips, and those irrelevant to our experiments were discarded.

Tracker, an open source video analysis and modeling tool, was used to extract pedestrian trajectories within the measurement area from our experiments. First, the video clips were divided into frame images at an interval of 5 FPS (0.2 s) in the software, we then marked the position point (i.e., the center point of the line connecting the two feet) of the pedestrian on each frame image by manually clicking the mouse, and finally these position points of the same pedestrian were linked frame by frame to form the complete trajectory. Given that the video was captured by the ultra-wide-angle lens of the fisheye camera, these frame images were calibrated for radial distortion (manifesting itself as a visible curvature in the project of straight lines) and perspective distortion (performing itself as each pixel with a different metric size) to convert image coordinates into real-world coordinates. The maximum systematic errors of these position points caused by insufficient calibration were estimated to be 0.07 m in the horizontal direction and 0.09 m in the vertical direction (Boltes et al., 2016). Ultimately, the pedestrian trajectories extracted from the videos of 27 experimental groups are plotted in Fig. 2, which contains 12 sets of trajectories stacked together for each condition.

3. Results

3.1. Analysis of the decision-making during subgroup movement

The theoretical movement states and preferences of subgroups when facing a static obstacle are illustrated in Fig. 3. On the one hand, subgroup members may pass through the obstacle in a congregated form, as shown in Fig. 3(a), which can be referred to as the maintaining state. Specifically, they move together to pass from a certain side of the obstacle with either left-side or right-side preference. On the other hand, subgroup members first temporarily split to pass through the obstacle, and then merge together to reach the terminal line, which can be called as the splitting–merging state in Fig. 3(b). The movement preference of subgroups in this state is more complicated: a greater number of members passing from the left side of the obstacle implies the left-side preference, vice versa for the right-side preference, and the same number of members passing from both sides is considered to be the equal-side preference. Based on the above theoretical definitions, the occurrences of movement states and preferences under different experimental groups are counted for subsequent quantitative analysis.

The effects of obstacle width, time pressure, and subgroup size on the movement state of subgroups are first investigated. In each round of experiments, subgroup members can only move in one of the maintaining and splitting–merging states, therefore, the proportions of movement states under different experimental groups are visualized in Fig. 4(a). It is obvious that the values of the three control variables have different influence degrees on the proportion of movement states. To analyze these effects more clearly, we adopt the control variable method and only change the value of one variable at a time while keeping other variables fixed. Fig. 4(b)–(d) reveal how the proportion of the splitting–merging state varies with the three control variables, which preliminarily shows that a wider obstacle width, a more urgent time pressure, and a larger subgroup size correspond to a higher proportion of the splitting–merging state. This may be due to the fact that changes in these control variables cause more members to make a decision to temporarily split from the subgroup because they are concerned about possible time delays of passing from one side of the obstacle in the maintaining state.

The movement preference of subgroups when facing a static obstacle is also worthy of statistical analysis. Fig. 5(a)–(c) demonstrate that subgroups in the maintaining state have a strong (more than 80%) right-side preference, regardless of variations in obstacle width, time pressure, and subgroup size. This is because "pedestrians walk on the right side" has long been regarded as a common-sense traffic habit in China, resulting in the majority of members defaulting to pass from the right side of the obstacle. Turning now to Fig. 5(d)–(e), subgroups in the splitting–merging state show a decreasing tendency of proportions of the equal-side, right-side, and left-side preferences when the obstacle width and time pressure are changed. However, it is essentially dependent on the difference in subgroup sizes in Fig. 5(f): subgroups of 2 members can only split with an equal-side preference, subgroups of 3 members can split with either left-side or right-side preference (the right-side preference is stronger), and subgroups of 4 members are able to split with all three preferences (the equal-side preference is extremely strong). This result is mainly influenced by the combination of congestion alleviation and habitual preferences, with the former having a higher priority. For subgroups of 3 members, they rely more on habitual preferences to pass from the right side since there must be one side with more members passing. For subgroups of 4 members, in most cases they choose the equal-side preference because this alleviates congestion on a certain side better compared to the left-side and right-side preferences.

3.2. Analysis of the motion behavior during subgroup movement

This section of the research is to analyze the motion behavior of subgroups when facing a static obstacle, and in particular, we focus on the differences in physical quantities between the maintaining and splitting–merging states. The first important physical quantity is distance, which is here specified as the path length of the pedestrian and can be calculated as the sum of the distances of adjacent trajectory points within the measurement area. The path lengths of subgroup members varying with different obstacle widths, time pressures, and subgroup sizes are explored, and Mann–Whitney–Wilcoxon U tests are used to test the differences between the data under certain conditions as well. Fig. 6(a) shows that the path lengths differ significantly at various obstacle widths because pedestrians need to detour for longer distances to pass through a wider obstacle. However, as illustrated in Fig. 6(b)–(c), there is no significant difference in path lengths at different time pressures and subgroup sizes, which means that analyzing the difference in path lengths of the two movement states only requires to be done at various obstacle widths. Fig. 6(d) reflects that the path lengths in the splitting–merging state are longer than those in the maintaining state, and the difference becomes more significant as the obstacle width extends. The components of the path length projected on the coordinate axes are further presented in Fig. 6(e)–(f), where there is a significant difference in components projected on the Y-axis, but almost no difference exists on the X-axis. This reveals that the difference in path lengths is largely triggered by more transverse displacements of subgroup members in the splitting–merging state.

The second vital physical quantity is time, which is embodied as the movement time of the pedestrian and can be defined as the time

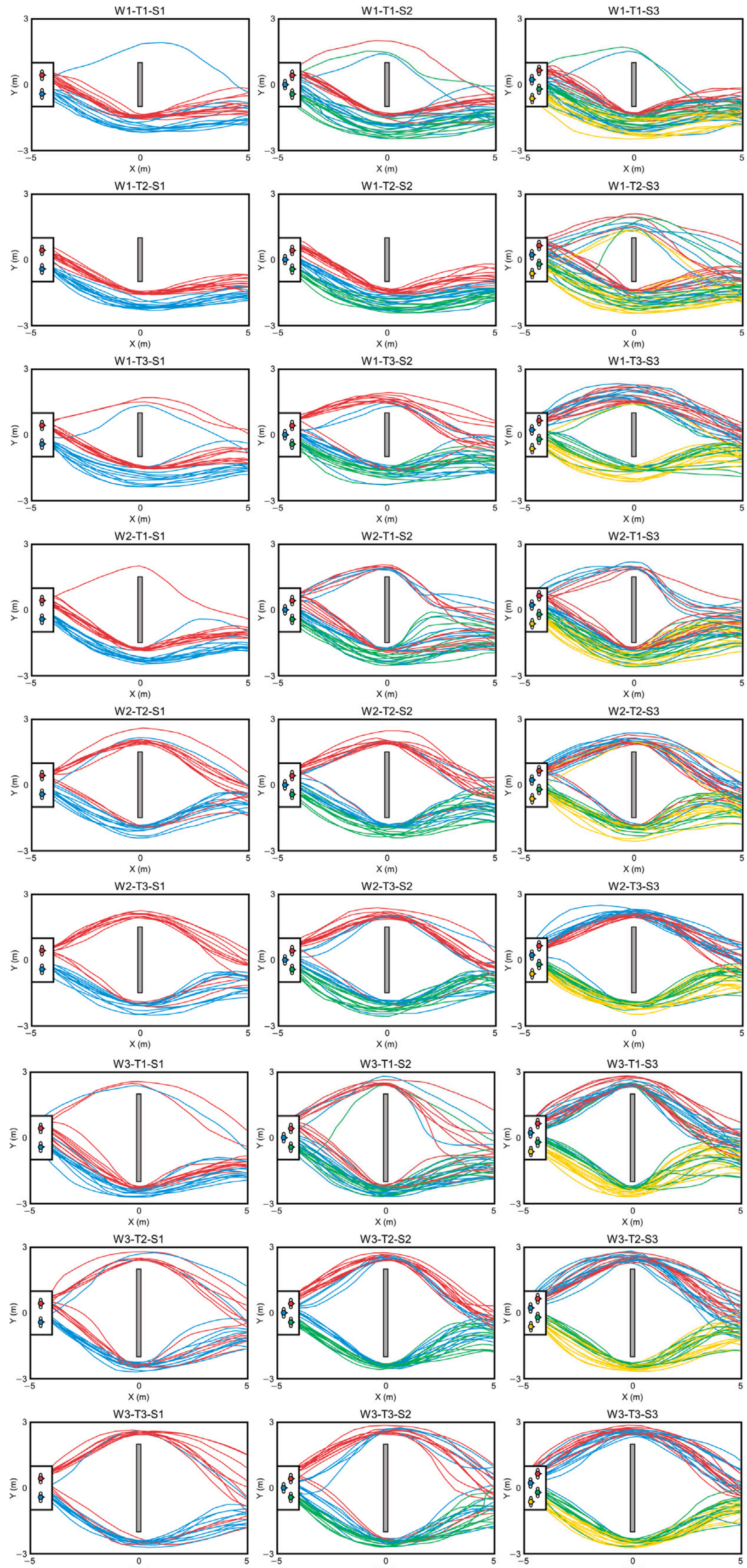

Fig. 2. Pedestrian trajectories under different experimental groups. The color of trajectories corresponds to the color of subgroup members, whose positions in the initial area are only used for example purposes.

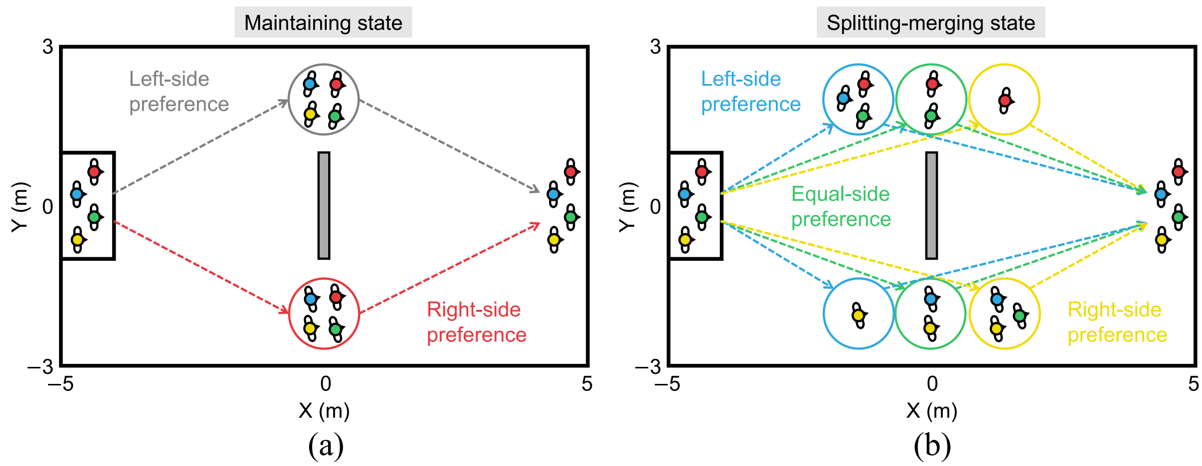

Fig. 3. Theoretical movement states and preferences of subgroups when facing a static obstacle. (a) The maintaining state with the left-side and right-side preferences. (b) The splitting–merging state with the left-side, equal-side, and right-side preferences.

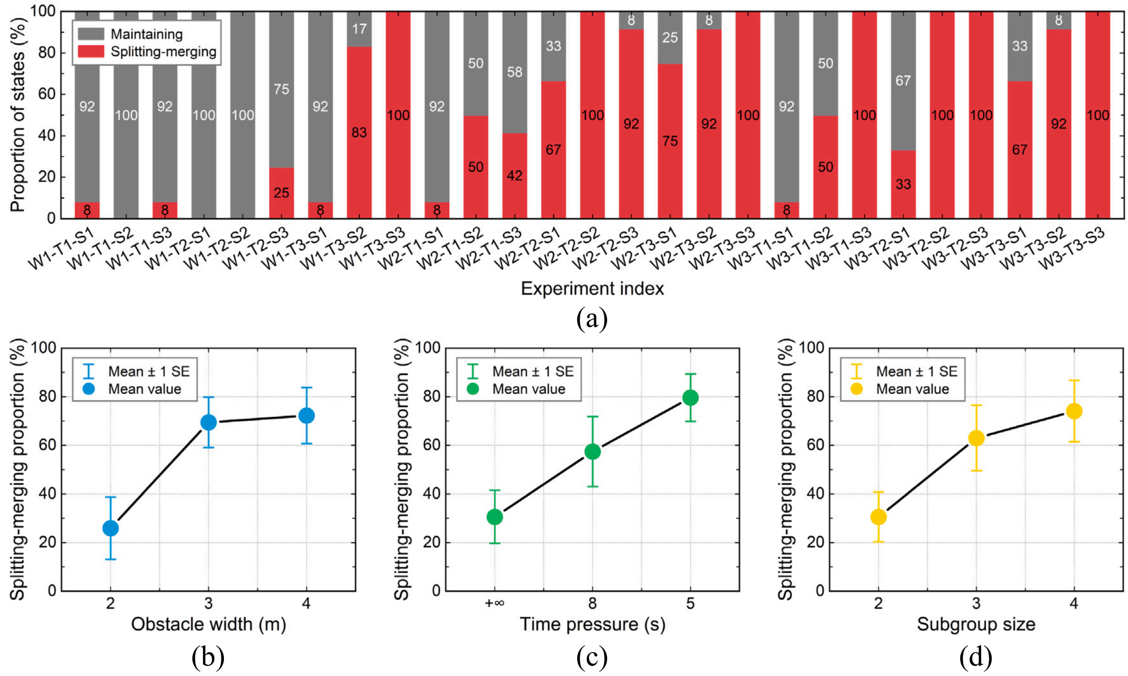

Fig. 4. Proportion analysis of movement states. (a) The proportions of the maintaining and splitting–merging states under different experimental groups. (b)–(d) The proportions of the splitting–merging state under different control variables. The solid circle and error bar represent the mean value and standard error, respectively.

consumed from leaving the initial area to reaching the terminal line. By using a similar method as before, the effects on the movement times of subgroup members under different obstacle widths, time pressures, and subgroup sizes are further analyzed. It can be seen from Fig. 7(a)–(c) that a more urgent time pressure inevitably triggers a significant decrease in movement times, and the change of subgroup size from 2 to 3 or 4 also leads to a significant increase in movement times, whereas there is a significant but relatively weak difference in movement times at various obstacle widths. For this, as shown in Fig. 7(d)–(f), we analyze the difference in movement times between the two movement states under different time pressures and subgroup sizes, which are the two control variables that have major effects. In most cases, the movement times in the splitting–merging state are slightly shorter than those in the maintaining state, but statistical tests confirm that there is almost no significant difference between the two movement states. In fact, although the congestion when passing through the obstacle in the splitting–merging state can be relatively alleviated compared to the maintaining state, the complex behavior of "merge first and then reach the terminal line together" may cause longer path lengths and more time delays in the subsequent stage than the simple behavior of "reach the terminal line together directly". This ultimately leads to the fact that moving in the splitting–merging state cannot significantly improve the evacuation efficiency as expected.

The third crucial physical quantity is speed, which is measured as the average speed of the pedestrian and can be determined as the path length divided by the movement time. To our knowledge, many studies of empirical observations have reached a consensus conclusion: the average speeds of subgroup members decrease with increasing subgroup size at normal densities (Nicolas & Hassan, 2021). Consequently, unlike the previous analysis of path length and movement time, we want to know whether the above conclusion still holds under the conditions where the other two control variables and movement states are different. Fig. 8(a)–(i) demonstrate the quantitative relationships between the average speed and the subgroup size under different

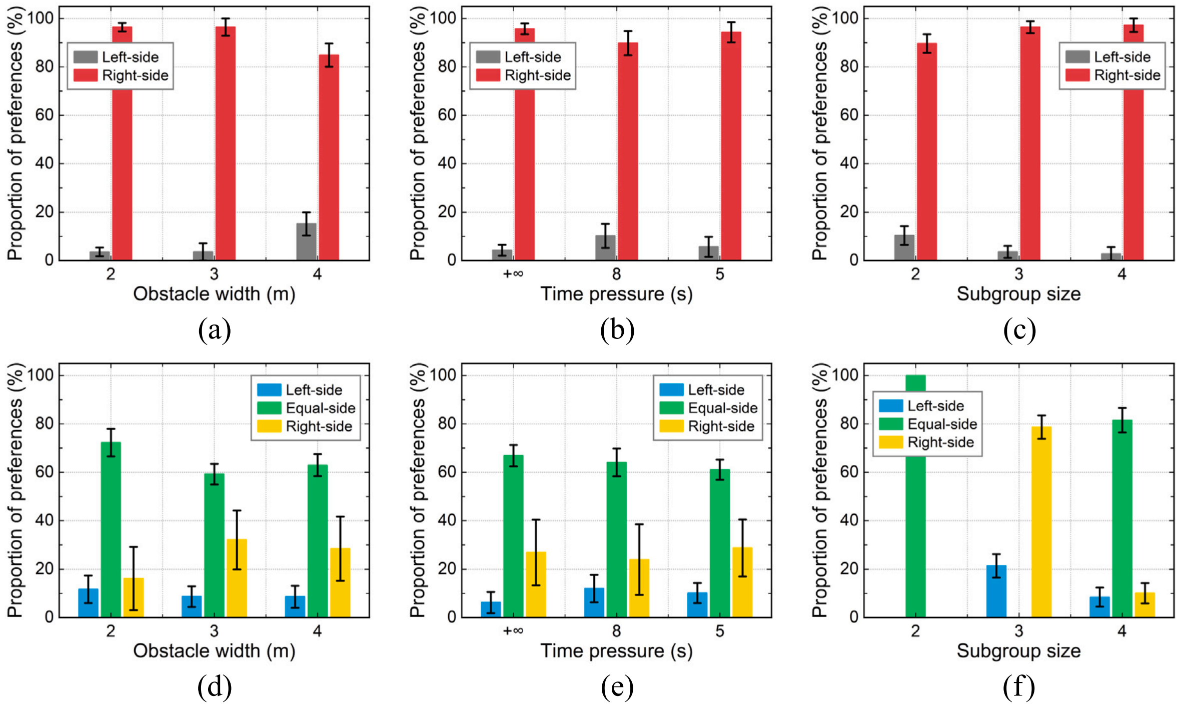

Fig. 5. Proportion analysis of movement preferences. (a)–(c) The proportions of the left-side and right-side preferences in the maintaining state under different control variables. (d)–(f) The proportions of the left-side, equal-side, and right-side preferences in the splitting–merging state under different control variables. The top line and whisker represent the mean value and standard error, respectively.

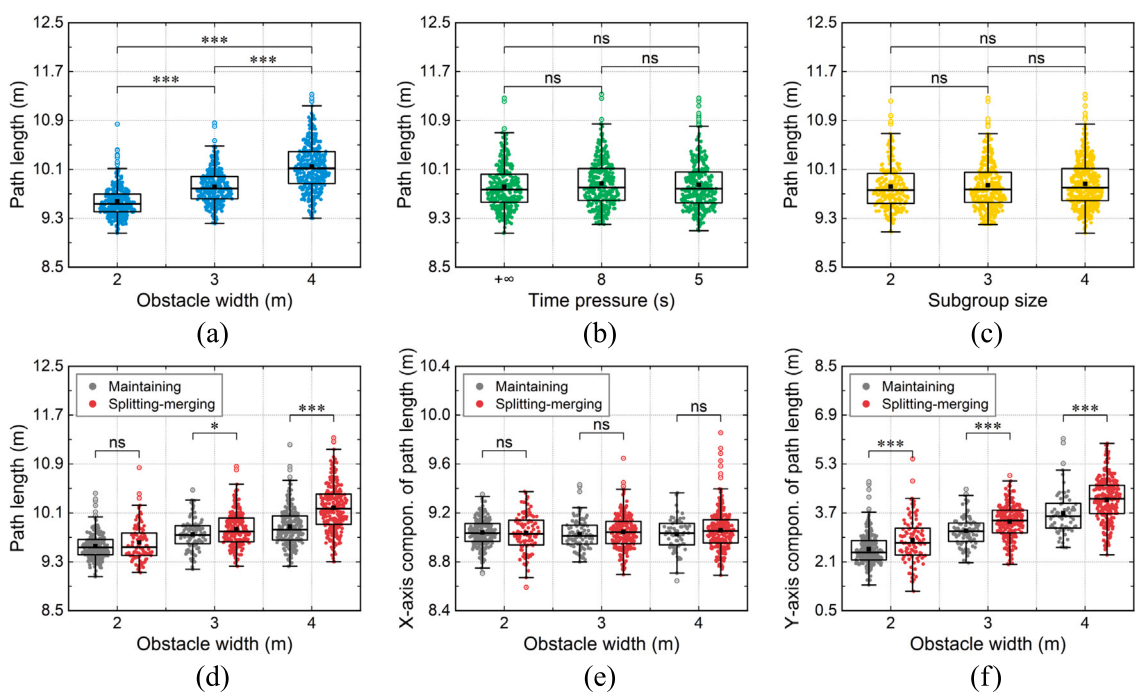

Fig. 6. Analysis and comparison of path lengths. (a)–(c) The path lengths of subgroup members under different control variables. (d)–(f) The path lengths, their X-axis components, and Y-axis components of the maintaining and splitting–merging states under different obstacle widths. The box indicates the data between the first and third quartiles, the whisker denotes the data within 1.5 times the interquartile range (IQR), and the central thick line and solid block represent the median line and mean value, respectively. $^{***}P < 0.001$; $^{**}P < 0.01$; $^{*}P < 0.05$; ns, $P > 0.05$.

obstacle widths and time pressures. The slopes in linear fitting curves (see Table 3) indicate that this negative correlation persists in the vast majority of cases, except for the anomaly of the positive correlation in Fig. 8(g), we guess that the faster average speeds of subgroups of 4 members are likely to be caused by accidental factors under certain experimental conditions. Despite that the proportions of the splitting–merging state differ significantly under various combinations of the other two control variables, however, they have almost no impact on this consensus conclusion. Therefore, we suggest that this conclusion can be further extended to most conditions of different obstacle widths, time pressures, and movement states.

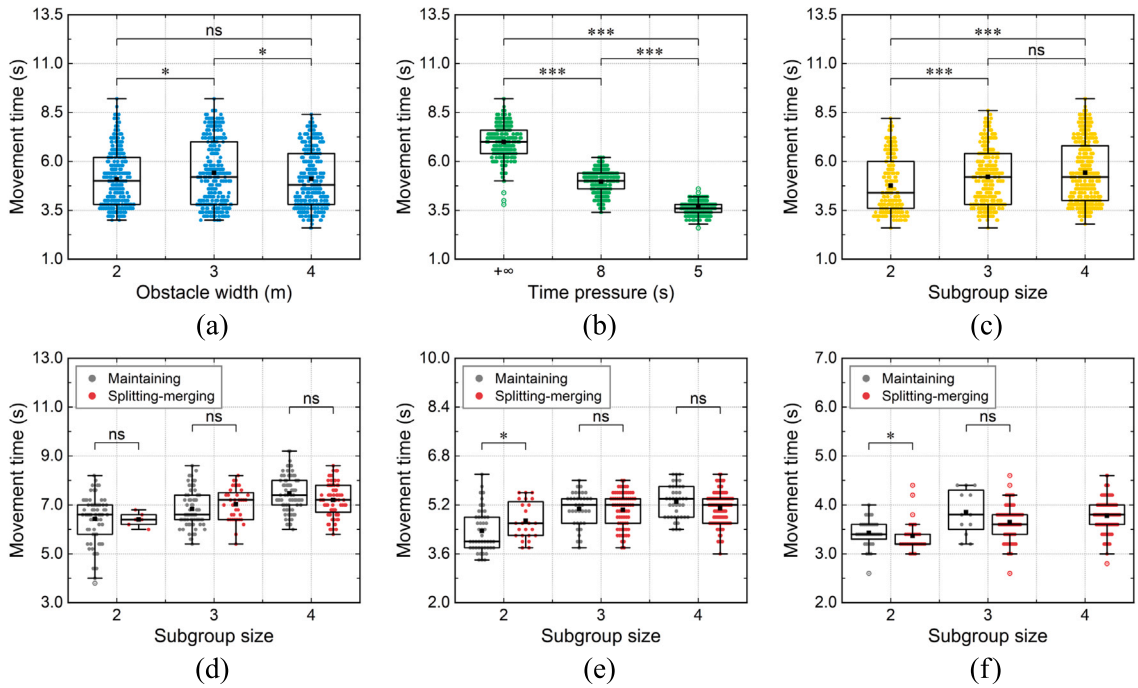

Fig. 7. Analysis and comparison of movement times. (a)–(c) The movement times of subgroup members under different control variables. (d)–(f) The movement times of the maintaining and splitting–merging states under different subgroup sizes when the time pressure manifests as non-, mild, and severe emergency situations. The box indicates the data between the first and third quartiles, the whisker denotes the data within 1.5 times the interquartile range (IQR), and the central thick line and solid block represent the median line and mean value, respectively. $^{***}P < 0.001$; $^{**}P < 0.01$; $^{*}P < 0.05$; ns, $P > 0.05$.

Table 3
Parameters and measurements of the linear fitting curves.

Obstacle width	Time pressure	Linear fitting curve		
		Slope	Intercept	Pearson correlation
2 m	+∞ s	−0.180	2.152	0.997
2 m	8 s	−0.223	2.804	0.839
2 m	5 s	−0.022	2.863	0.778
3 m	+∞ s	−0.029	1.481	0.863
3 m	8 s	−0.063	2.229	0.721
3 m	5 s	−0.089	3.165	0.856
4 m	+∞ s	+0.021	1.467	0.683
4 m	8 s	−0.050	2.416	0.801
4 m	5 s	−0.117	3.349	0.892

3.3. Analysis of the splitting–merging state during subgroup movement

Owing to the fact that many studies have explored the behavioral characteristics of subgroups when moving in the maintaining state (Karamouzas & Overmars, 2012; Zanlungo et al., 2015), we now turn to concentrate on the splitting–merging state during subgroup movement. The splitting process implies that subgroup members separate from a congregated form and move to both sides of the obstacle, and the merging process means that subgroup members move from both sides of the obstacle to reorganize into a congregated form. Here, the congregated form is defined as the distances from subgroup members to the centroid are lower than a threshold value (Moussaïd et al., 2010), which can be approximated as $(S-1)/2$ m based on the data collection at low densities, where S is the subgroup size. From this, under the conditions of different obstacle widths, time pressures, and subgroup sizes, Fig. 9(a)–(f) exhibit the centroid positions of subgroup members at the start of the splitting process and at the end of the merging process, along with the boxplots of centroid positions projected on the X-axis. As the obstacle width extends, Fig. 9(a) and (d) reflect that the centroid positions are farther away from the obstacle in both situations, probably to minimize the detour behavior of sharp turns. As shown in Fig. 9(b) and (e), the exacerbation of time pressure has almost no clear effect on the distances from the centroid positions to the obstacle at the start of the splitting process, but significantly increases those at the end of the merging process. This is because when time pressure becomes more urgent, the willingness of subgroup members to reach the terminal line with a shorter path is given a higher dominance than the willingness to merge with other members. With the growing size of subgroups in Fig. 9(c) and (f), the centroid positions are closer to the obstacle in both situations since a greater subgroup size corresponds to a larger spatial range of the congregated form, which makes it harder to split and easier to merge than subgroups with a smaller size.

Under the conditions of different obstacle widths, time pressures, and subgroup sizes, we further analyze and compare the movement times and average speeds of subgroup members in the splitting and merging processes. The widening of obstacle width enhances the transverse and longitudinal displacements of subgroup members in both processes, which leads to a significant extension of movement times in Fig. 10(a), but the decline of average speeds in Fig. 10(d) is probably related to the deceleration behavior triggered by the larger detour angle. Fig. 10(b) and (e) indicate that as the time pressure intensifies, the average speeds of subgroup members inevitably increase in both processes, resulting in a significant decrease in movement times. Due to the fact that the centroid positions of subgroups with a larger size are closer to the obstacle has been pointed out in Fig. 9(c) and (f), this induces a reduction in movement times in Fig. 10(c), while the decrease in average speeds with increasing subgroup size in Fig. 10(f) has been proven to be independent of other experimental conditions. It can be noticed that in most cases the movement times consumed in the merging process are significantly longer than those in the splitting process, but there is little significant difference in average speeds between the two processes. This reveals that the difference at the temporal level is largely influenced by the centroid positions at the start of the splitting process and at the end of the merging process, which determines the path lengths corresponding to the two processes.

In addition, the effects of the movement preference on the splitting and merging processes are also an issue worthy of consideration.

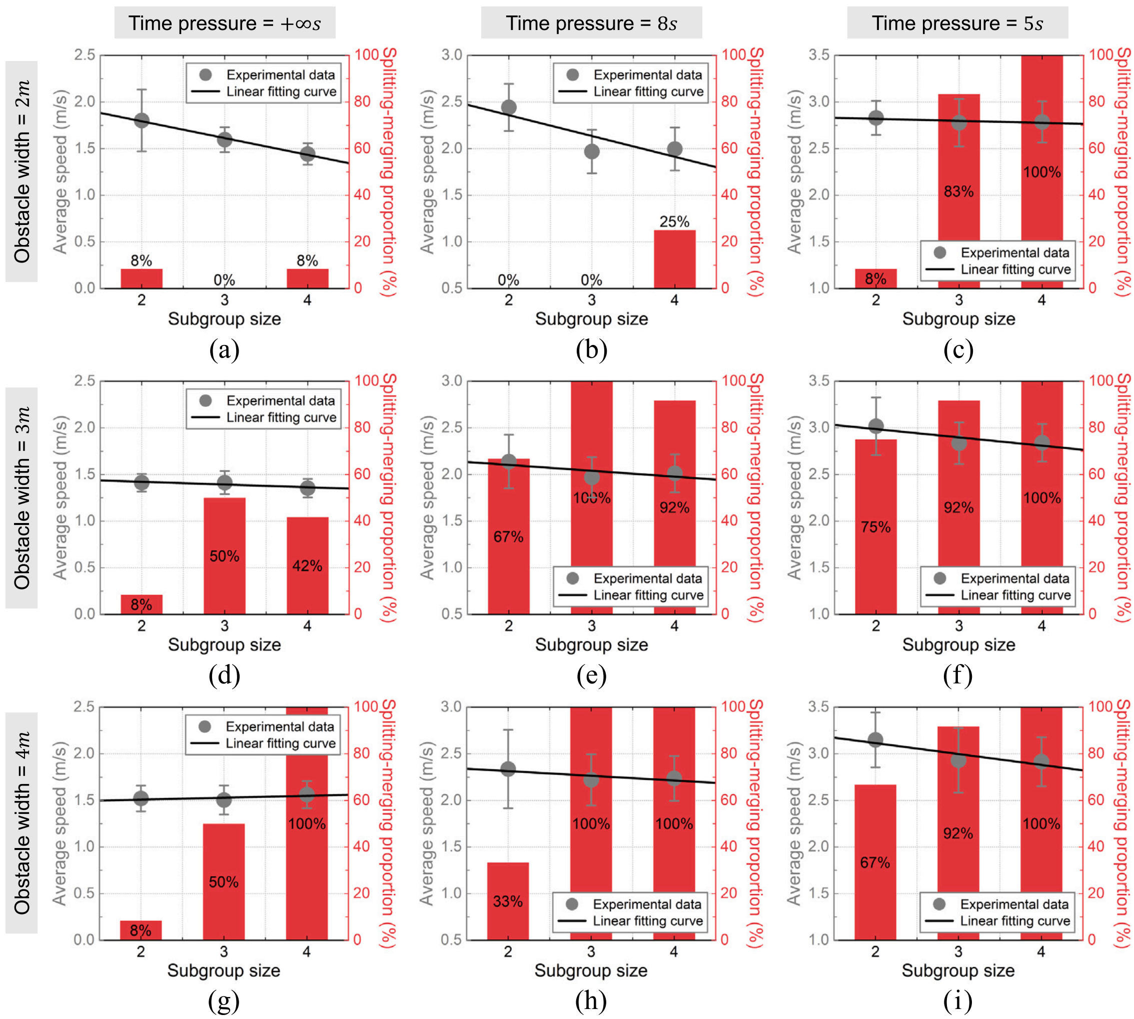

Fig. 8. Quantitative relationships between the average speed and the subgroup size under different obstacle widths and time pressures. (a) Obstacle width = 2 m and Time pressure = +∞ s. (b) Obstacle width = 2 m and time pressure = 8 s. (c) Obstacle width = 2 m and time pressure = 5 s. (d) Obstacle width = 3 m and time pressure = +∞ s. (e) Obstacle width = 3 m and time pressure = 8 s. (f) Obstacle width = 3 m and time pressure = 5 s. (g) Obstacle width = 4 m and time pressure = +∞ s. (h) Obstacle width = 4 m and time pressure = 8 s. (i) Obstacle width = 4 m and time pressure = 5 s. The red column represents the proportion of the splitting–merging state under each experimental group.

Fig. 11(a)–(b) present the centroid positions of subgroups with various movement preferences at the start of the splitting process and at the end of the merging process, respectively. It can be seen from these boxplots that the centroid positions projected on the Y-axis are significantly different, whose arrangement order exactly corresponds to the movement preference. Notably, the difference in centroid positions at the end of the merging process is much larger than that at the start of the splitting process, which is more significant under the equal-side and right-side preferences in Fig. 11(c). In the ideal case, the mean value of the centroid positions projected on the Y-axis for subgroups with an equal-side preference should be near $y = 0$ m. In the actual case, the mean value ($y = 0.124$ m) at the start of the splitting process is very close to $y = 0$ m, however, the mean value ($y = -0.439$ m) at the end of the merging process is clearly biased to the right side. The reason might be that subgroup members are more inclined to merge from the positions biased to the right side before reaching the terminal line (because we do not require that the center of the terminal line must be reached), resulting in the fact that for subgroups with any preference in Fig. 11(d), the displacements projected on the Y-axis of members passing from the left side in the merging process are significantly longer than those of members passing from the right side. If this position preference can be eliminated in Fig. 11(e), for subgroups with an equal-side preference, there is no significant difference in displacements projected on the Y-axis of members passing from the left and right sides in the merging process. However, for subgroups with either left-side or right-side preference, the part with fewer members passing from one side should move longer displacements (also with faster speeds) to approach the part with more members passing from another side, which reveals the herding effect of subgroup members in the merging process.

4. Conclusion

This paper introduces three control variables of obstacle width, time pressure, and subgroup size into controlled experiments to explore the decision-making and motion behavior of subgroups when facing a static obstacle during movement. By analyzing the collected experimental data, a series of conclusions are summarized as follows: (1) A wider obstacle width, a more urgent time pressure, and a larger subgroup size correspond to a higher proportion of the splitting–merging state. (2) Subgroups in the maintaining state have a strong right-side preference, whereas the movement preference in the splitting–merging state is highly dependent on the difference in subgroup sizes. (3) The path lengths in the splitting–merging state are longer than those in the maintaining state, and the difference becomes more significant as the obstacle width extends. (4) The movement times in the splitting–merging state are slightly shorter than those in the maintaining state, but there is almost no significant difference between the two movement

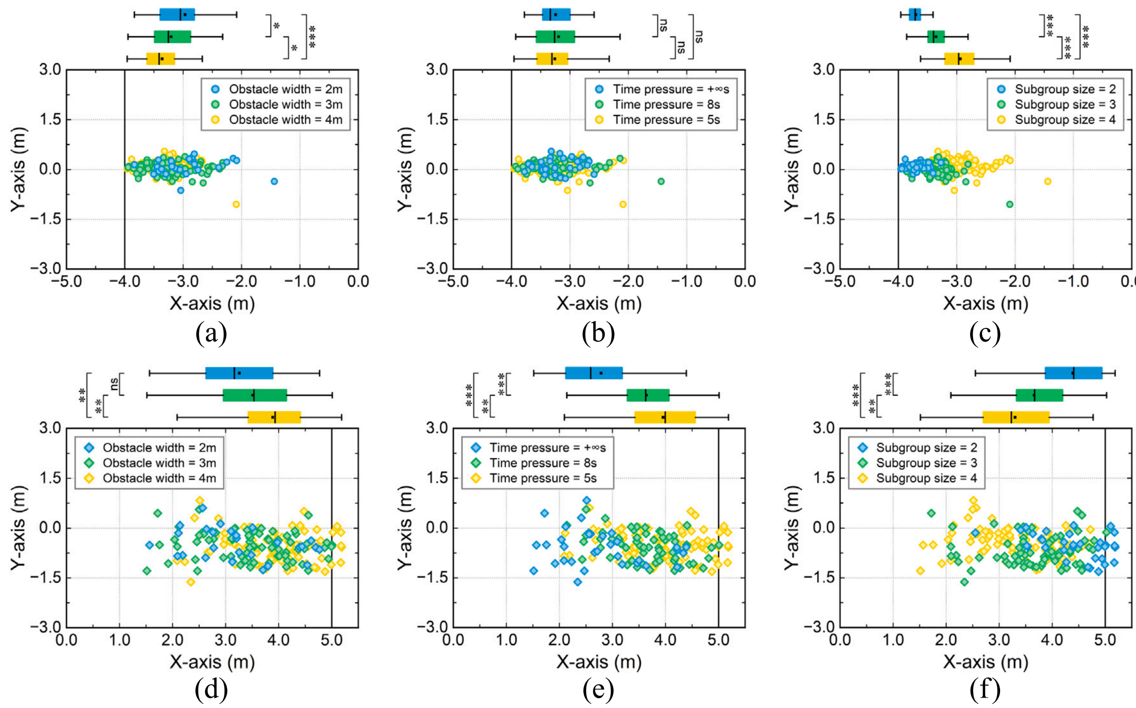

Fig. 9. Analysis and comparison of centroid positions. (a)–(c) The centroid positions at the start of the splitting process under different control variables. (d)–(f) The centroid positions at the end of the merging process under different control variables. The box indicates the data between the first and third quartiles, the whisker denotes the data within 1.5 times the interquartile range (IQR), and the central thick line and solid block represent the median line and mean value, respectively. *** $P < 0.001$; ** $P < 0.01$; * $P < 0.05$; ns, $P > 0.05$.

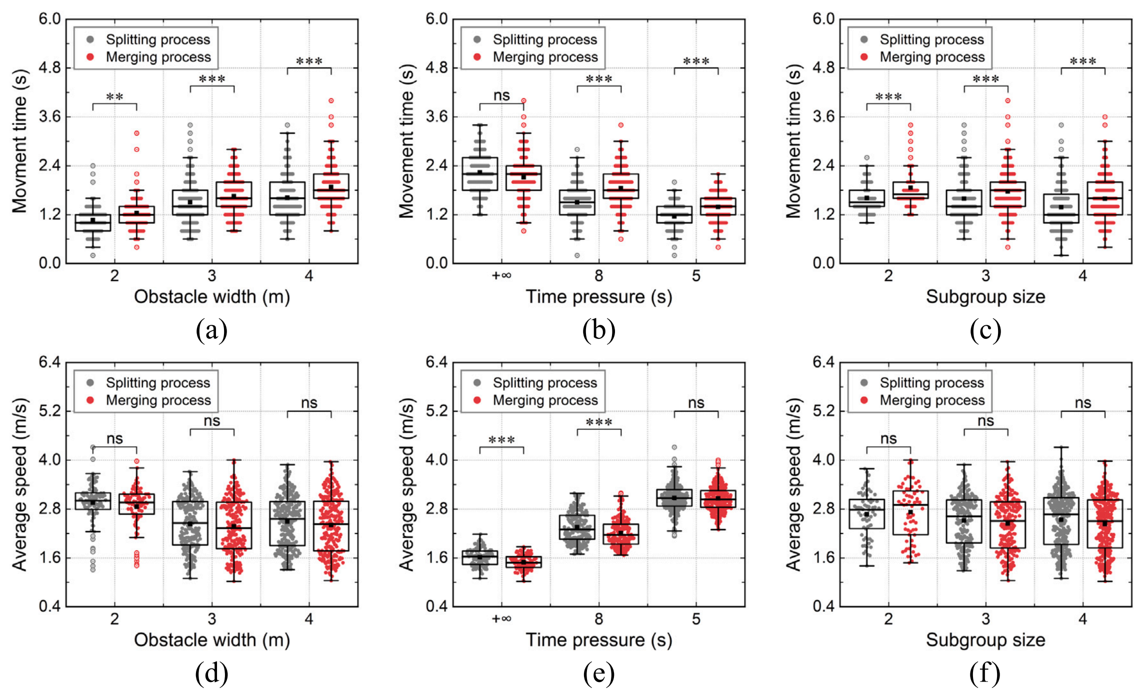

Fig. 10. Analysis and comparison of movement times and speeds. (a)–(c) The movement times in the splitting and merging processes under different control variables. (d)–(f) The movement speeds in the splitting and merging processes under different control variables. The box indicates the data between the first and third quartiles, the whisker denotes the data within 1.5 times the interquartile range (IQR), and the central thick line and solid block represent the median line and mean value, respectively. *** $P < 0.001$; ** $P < 0.01$; * $P < 0.05$; ns, $P > 0.05$.

states. (5) The conclusion that the average speeds of subgroup members decrease with increasing subgroup size at normal densities can be further extended to most conditions of different obstacle widths, time pressures, and movement states. (6) The obstacle width, time pressure, and subgroup size have various influence degrees on the centroid positions, movement times, and average speeds of subgroup members in the splitting and merging processes. (7) The movement preference has a more significant effect on the difference in centroid positions at the end of the merging process, which is manifested as the herding effect of subgroup members in the merging process.

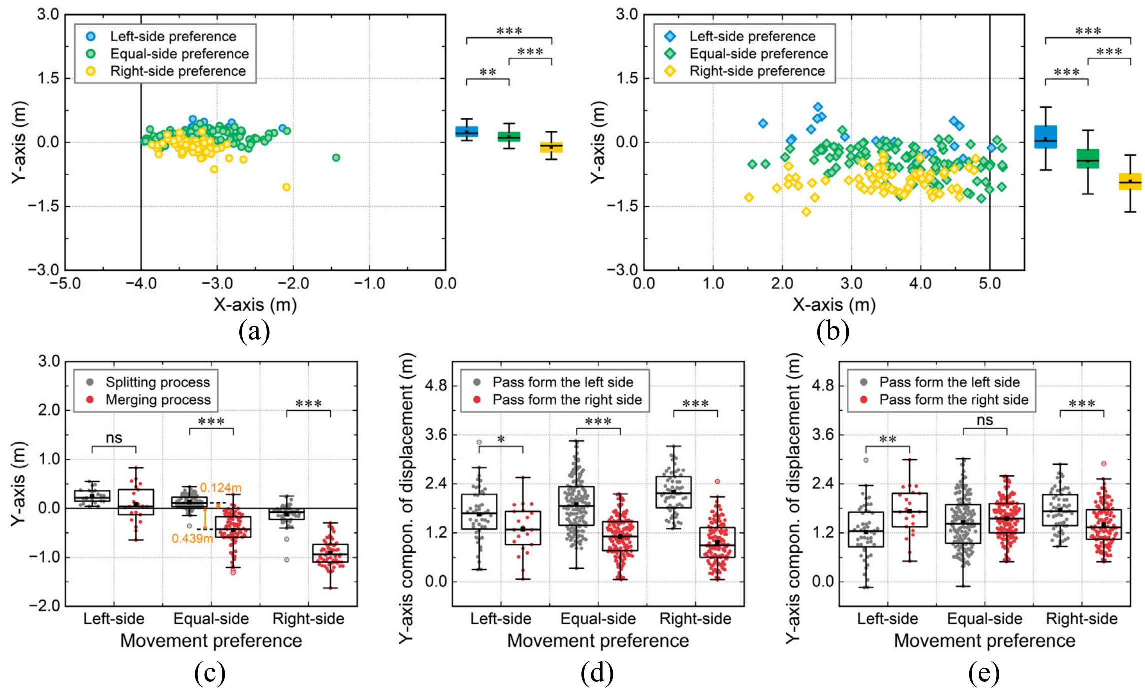

Fig. 11. Analysis of the splitting and merging processes under different movement preferences. (a)–(b) The centroid positions at the start of the splitting process and at the end of the merging process. (c) The centroid positions projected on the Y-axis at the start of the splitting process and at the end of the merging process. (d)–(e) The displacements (with and without the position preference) projected on the Y-axis of members passing from the left and right sides in the merging process. The box indicates the data between the first and third quartiles, the whisker denotes the data within 1.5 times the interquartile range (IQR), and the central thick line and solid block represent the median line and mean value, respectively. $^{***}P < 0.001$; $^{**}P < 0.01$; $^{*}P < 0.05$; ns, $P > 0.05$.

These conclusions are beneficial to help researchers better understand the decision-making and motion behavior of subgroups, and serve as empirical evidence to guide the construction of more realistic subgroup models. Despite that the movement patterns of subgroups in the maintaining state have been successfully reproduced by many existing models, such as those based on the cohesion effect (Huang et al., 2018) and the leader-follower principle (Xie et al., 2022). However, the splitting–merging state has rarely been considered in modeling and simulations, but a large number of field observations and this work have confirmed that it cannot be neglected. How the conditions that induce different movement states and preferences and the parameters that characterize different motion behaviors can be incorporated into subgroup models will become a challenging issue. We suggest that the perception of visual information, the panic level of individuals, and the cohesive coefficient related to size might bring potential solutions for quantitative representation in subsequent modeling. In summary, this work undoubtedly provides persuasive findings for exploring the behavioral mechanism of subgroups when interacting with static obstacles. In the future, how subgroups make decisions and move when facing dynamic obstacles (e.g., oncoming pedestrians Yi et al., 2023) is worthy of further exploration. We also hope that this work will contribute valuable insights to a wide range of fields such as behavioral cognition, safety science, and architectural design.

CRediT authorship contribution statement

Wenhan Wu: Data curation, Investigation, Formal analysis, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **Wenfeng Yi:** Data curation, Methodology, Writing – review & editing. **Xiaolu Wang:** Data curation, Funding acquisition, Resources. **Erhui Wang:** Data curation, Investigation. **Xiaoping Zheng:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

Bode, N. W. F., Holl, S., Mehner, W., & Seyfried, A. (2015). Disentangling the impact of social groups on response times and movement dynamics in evacuations. In G. Xiao (Ed.), *PLOS One*, *10*(3), Article e0121227. http://dx.doi.org/10.1371/journal.pone.0121227.

Boltes, M., Holl, S., Tordeux, A., Seyfried, A., Schadschneider, A., & Lang, U. (2016). Influences of extraction techniques on the quality of measured quantities of pedestrian characteristics. In *Proceedings of pedestrian and evacuation dynamics 2016* (pp. 540–547).

Chen, S., Fu, L., Fang, J., & Yang, P. (2019). The effect of obstacle layouts on pedestrian flow in corridors: An experimental study. *Physica A. Statistical Mechanics and its Applications*, *534*, Article 122333. http://dx.doi.org/10.1016/j.physa.2019.122333.

Ding, Z., Shen, Z., Guo, N., Zhu, K., & Long, J. (2020). Evacuation through area with obstacle that can be stepped over: experimental study. *Journal of Statistical Mechanics: Theory and Experiment*, *2020*(2), Article 023404. http://dx.doi.org/10.1088/1742-5468/ab6a01.

Do, T., Haghani, M., & Sarvi, M. (2016). Group and single pedestrian behavior in crowd dynamics. *Transportation Research Record: Journal of the Transportation Research Board*, *2540*(1), 13–19. http://dx.doi.org/10.3141/2540-02.

Dong, H., Zhou, M., Wang, Q., Yang, X., & Wang, F.-Y. (2020). State-of-the-art pedestrian and evacuation dynamics. *IEEE Transactions on Intelligent Transportation Systems*, *21*(5), 1849–1866. http://dx.doi.org/10.1109/tits.2019.2915014.

Duives, D., Daamen, W., & Hoogendoorn, S. (2014). Influence of group size and group composition on the adhered distance headway. *Transportation Research Procedia*, *2*, 183–188. http://dx.doi.org/10.1016/j.trpro.2014.09.026.

Feng, Y., Duives, D., Daamen, W., & Hoogendoorn, S. (2021). Data collection methods for studying pedestrian behaviour: A systematic review. *Building and Environment*, *187*, Article 107329. http://dx.doi.org/10.1016/j.buildenv.2020.107329.

Fu, L., Cao, S., Shi, Y., Chen, S., Yang, P., & Fang, J. (2019). Walking behavior of pedestrian social groups on stairs: A field study. *Safety Science*, *117*, 447–457. http://dx.doi.org/10.1016/j.ssci.2019.04.048.

Fu, L., Shi, Q., Qin, H., Zhang, Y., & Shi, Y. (2022). Analysis of movement behavior of pedestrian social groups through a bottleneck. *Physica A. Statistical Mechanics and its Applications*, *608*, Article 128257. http://dx.doi.org/10.1016/j.physa.2022.128257.

Gorrini, A., Crociani, L., Vizzari, G., & Bandini, S. (2019). Crossing behaviour of social groups: Insights from observations at non-signalised intersection. In *Traffic and granular flow'17* (pp. 443–450). Springer International Publishing, http://dx.doi.org/10.1007/978-3-030-11440-4_48.

Haghani, M., & Sarvi, M. (2018). Crowd behaviour and motion: Empirical methods. *Transportation Research, Part B (Methodological)*, *107*, 253–294. http://dx.doi.org/10.1016/j.trb.2017.06.017.

Haghani, M., Sarvi, M., Shahhoseini, Z., & Boltes, M. (2019). Dynamics of social groups' decision-making in evacuations. *Transportation Research Part C (Emerging Technologies)*, *104*, 135–157. http://dx.doi.org/10.1016/j.trc.2019.04.029.

Helbing, D., & Johansson, A. (2009). Pedestrian, crowd and evacuation dynamics. In *Encyclopedia of complexity and systems science* (pp. 6476–6495). Springer New York, http://dx.doi.org/10.1007/978-0-387-30440-3_382.

Hu, Y., Zhang, J., Song, W., & Bode, N. W. (2021). Social groups barely change the speed-density relationship in unidirectional pedestrian flow, but affect operational behaviours. *Safety Science*, *139*, Article 105259. http://dx.doi.org/10.1016/j.ssci.2021.105259.

Huang, L., Gong, J., Li, W., Xu, T., Shen, S., Liang, J., Feng, Q., Zhang, D., & Sun, J. (2018). Social force model-based group behavior simulation in virtual geographic environments. *ISPRS International Journal of Geo-Information*, *7*(2), 79. http://dx.doi.org/10.3390/ijgi7020079.

Jazwinski, C. H., & Walcheski, C. H. (2011). At the mall with children: Group size and pedestrian economy of movement. *Environment and Behavior*, *43*(3), 363–386. http://dx.doi.org/10.1177/0013916510364461.

Jia, X., Feliciani, C., Yanagisawa, D., & Nishinari, K. (2019). Experimental study on the evading behavior of individual pedestrians when confronting with an obstacle in a corridor. *Physica A. Statistical Mechanics and its Applications*, *531*, Article 121735. http://dx.doi.org/10.1016/j.physa.2019.121735.

Jiang, L., Li, J., Shen, C., Yang, S., & Han, Z. (2014). Obstacle optimization for panic flow - Reducing the tangential momentum increases the escape speed. In Z.-K. Gao (Ed.), *PLOS One*, *9*(12), Article e115463. http://dx.doi.org/10.1371/journal.pone.0115463.

Karamouzas, I., & Overmars, M. (2012). Simulating and evaluating the local behavior of small pedestrian groups. *IEEE Transactions on Visualization and Computer Graphics*, *18*(3), 394–406. http://dx.doi.org/10.1109/tvcg.2011.133.

Li, H., Zhang, J., Xia, L., Song, W., & Bode, N. W. (2019). Comparing the route-choice behavior of pedestrians around obstacles in a virtual experiment and a field study. *Transportation Research Part C (Emerging Technologies)*, *107*, 120–136. http://dx.doi.org/10.1016/j.trc.2019.08.012.

Lombardi, M., Warren, W. H., & di Bernardo, M. (2020). Nonverbal leadership emergence in walking groups. *Scientific Reports*, *10*(1), http://dx.doi.org/10.1038/s41598-020-75551-2.

Moussaïd, M., Helbing, D., Garnier, S., Johansson, A., Combe, M., & Theraulaz, G. (2009). Experimental study of the behavioural mechanisms underlying self-organization in human crowds. *Proceedings of the Royal Society B: Biological Sciences*, *276*(1668), 2755–2762. http://dx.doi.org/10.1098/rspb.2009.0405.

Moussaïd, M., Perozo, N., Garnier, S., Helbing, D., & Theraulaz, G. (2010). The walking behaviour of pedestrian social groups and its impact on crowd dynamics. In G. Chirico (Ed.), *PLOS One*, *5*(4), Article e10047. http://dx.doi.org/10.1371/journal.pone.0010047.

Nicolas, A., & Hassan, F. H. (2021). Social groups in pedestrian crowds: review of their influence on the dynamics and their modelling. *Transportmetrica A: Transport Science*, *19*(1), http://dx.doi.org/10.1080/23249935.2021.1970651.

Ren, J., Mao, Z., Zhang, D., Gong, M., & Zuo, S. (2022). Experimental study of crowd evacuation dynamics considering small group behavioral patterns. *International Journal of Disaster Risk Reduction*, *80*, Article 103228. http://dx.doi.org/10.1016/j.ijdrr.2022.103228.

Shi, X., Ye, Z., Shiwakoti, N., Tang, D., & Lin, J. (2019). Examining effect of architectural adjustment on pedestrian crowd flow at bottleneck. *Physica A. Statistical Mechanics and its Applications*, *522*, 350–364. http://dx.doi.org/10.1016/j.physa.2019.01.086.

Singh, H., Arter, R., Dodd, L., Langston, P., Lester, E., & Drury, J. (2009). Modelling subgroup behaviour in crowd dynamics DEM simulation. *Applied Mathematical Modelling*, *33*(12), 4408–4423. http://dx.doi.org/10.1016/j.apm.2009.03.020.

von Krüchten, C., & Schadschneider, A. (2017). Empirical study on social groups in pedestrian evacuation dynamics. *Physica A. Statistical Mechanics and its Applications*, *475*, 129–141. http://dx.doi.org/10.1016/j.physa.2017.02.004.

Wang, W., Zhang, J., Li, H., & Xie, Q. (2020). Experimental study on unidirectional pedestrian flows in a corridor with a fixed obstacle and a temporary obstacle. *Physica A. Statistical Mechanics and its Applications*, *560*, Article 125188. http://dx.doi.org/10.1016/j.physa.2020.125188.

Wu, W., Yi, W., Wang, X., & Zheng, X. (2023). A force-based model for adaptively controlling the spatial configuration of pedestrian subgroups at non-extreme densities. *Transportation Research Part C (Emerging Technologies)*, *152*, Article 104154. http://dx.doi.org/10.1016/j.trc.2023.104154.

Wu, W., & Zheng, X. (2023). A systematic analysis of subgroup research in pedestrian and evacuation dynamics. *IEEE Transactions on Intelligent Transportation Systems*, 1–22. http://dx.doi.org/10.1109/tits.2023.3318417.

Xie, W., Lee, E. W. M., Cheng, Y., Shi, M., Cao, R., & Zhang, Y. (2020). Evacuation performance of individuals and social groups under different visibility conditions: Experiments and surveys. *International Journal of Disaster Risk Reduction*, *47*, Article 101527. http://dx.doi.org/10.1016/j.ijdrr.2020.101527.

Xie, W., Lee, E. W. M., & Lee, Y. Y. (2022). Simulation of spontaneous leader–follower behaviour in crowd evacuation. *Automation in Construction*, *134*, Article 104100. http://dx.doi.org/10.1016/j.autcon.2021.104100.

Ye, R., Fang, Z., Lian, L., Wang, Q., Zeng, G., Cao, S., Zhang, J., & Song, W. (2021). Traffic dynamics of uni- and bidirectional pedestrian flows including dyad social groups in a ring-shaped corridor. *Journal of Statistical Mechanics: Theory and Experiment*, *2021*(2), Article 023406. http://dx.doi.org/10.1088/1742-5468/abdc1a.

Yi, W., Wu, W., Wang, X., & Zheng, X. (2023). Modeling the mutual anticipation in human crowds with attention distractions. *IEEE Transactions on Intelligent Transportation Systems*, *24*(9), 10108–10117. http://dx.doi.org/10.1109/tits.2023.3268315.

Zanlungo, F., Brščić, D., & Kanda, T. (2015). Spatial-size scaling of pedestrian groups under growing density conditions. *Physical Review E*, *91*(6), Article 062810. http://dx.doi.org/10.1103/physreve.91.062810.

Zhao, Y., Lu, T., Fu, L., Wu, P., & Li, M. (2020). Experimental verification of escape efficiency enhancement by the presence of obstacles. *Safety Science*, *122*, Article 104517. http://dx.doi.org/10.1016/j.ssci.2019.104517.